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Gamma dose measurements in the rabbit tube of the UTR-10

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GAMMA DOSE MEASUREMENTS IN THE RABBIT TUBE

OF THE UTR-10

by

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INTRODUCTION

When a mixed radiation field is to be used for the study of radiation effects, it is often desirable to know the gamma dose as well as the neutron flux received by the sample. For effects such as radiation induced polymerization of organic compounds or the production of color centers in ionic crystals by radiation, it is often more important to know the gamma dose which the sample has absorbed than the neutron flux present.

The object of this investigation is to determine the gamma dose rates in the rabbit tube of the UTR-10 and attempt to develope a mathematical expression relating these gamma dose rates to the power level, time of operation at power, and the sample position in the rabbit.

The rabbit tube was chosen for this study because it provides rapid entry and exit from the radiation field and as a result is usually used when sample size permits.

The gamma dose rates in roentgens per hour were determined by means of silver-activated glass dosimeters and relationships between the dose rate and the power level, time of operation and prerun dose levels were determined.

DOSIMETRY SYSTEM

Dose measurements were made using silver-activated phosphate glass needle dosimeters which are available under the trade name Fluorod[1]. This dosimeter is a glass cylinder of silver-activated glass, 1 mm in diameter and 6 mm long. Its composition in weight percent is 50% $Al(PO_3)_3$, 25% $Ba(PO_3)_2$, 25% KPO_3 with an addition of 8% $AgPO_3$.

The response of Fluorods is due to radiophotoluminescence of silver atoms (5). When silver is widely dispersed in low concentrations the atoms will emit orange luminescence at a rate proportional to their concentration when excited by ultraviolet light. The emission bands of the unirradiated glass are due to silver ions dispersed in the glass matrix. The emission bands of the irradiated glass correspond to those of atomic silver. The luminescence centers--reduced silver atoms--are formed when silver ions trap electrons which have been freed from the crystal's components by radiation and are formed at a rate proportional to the absorbed gamma dose. The electrons thus trapped by the silver ions are apparently held more tightly than those in F-centers since they are more stable to light and increased temperatures. The principal effect of light absorption by these centers apparently is not the freeing of the electron with the resultant destruction of the center, but the raising of the electron to an excited state from which it returns by luminescence emission.

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[1]Bausch and Lomb, Rochester, New York.

The growth of the luminescence centers, and consequently the total luminescence, does not reach its peak for twenty four hours after irradiation. Therefore, after exposure it is desirable to allow time for equilibrium to be reached. Twenty-four hours were allowed before readings were made (6).

Fluorods give a linear response in the range from 10 roentgens to 2 X 10^4 roentgens of absorbed dose without any special treatment. It has been reported that the linear response region can be extended up to an absorbed dose of 4 X 10^5 roentgens when the rods are heated for one hour at 325°C after the dose has been absorbed (3). When heated at 325°C the luminescence centers are relatively unaffected, while the color centers which have also been produced in the glass matrix are removed. The heat treatment was not necessary in this study since the range without the extension from the heat treatment was sufficient for power levels up to 10 kilowatts, full power for the UTR-10.

The rods are relatively dose rate independent, however, they do show some dose rate dependence. The dose rate dependence has been investigated in two independent studies (2, 4) which are in close agreement. The dose rate dependence found by Kondo is shown in Figure 1. Correction of the dose rates was based on this figure and the dose rates used for dosing the standards.

The dosimeter glass has the desirable property of being energy independent over a very wide range of energies. However, it has a very marked energy dependence which has a 21-1 ratio of luminescent response when comparing 50 kev x-rays to Co^{60} gamma rays. In order to

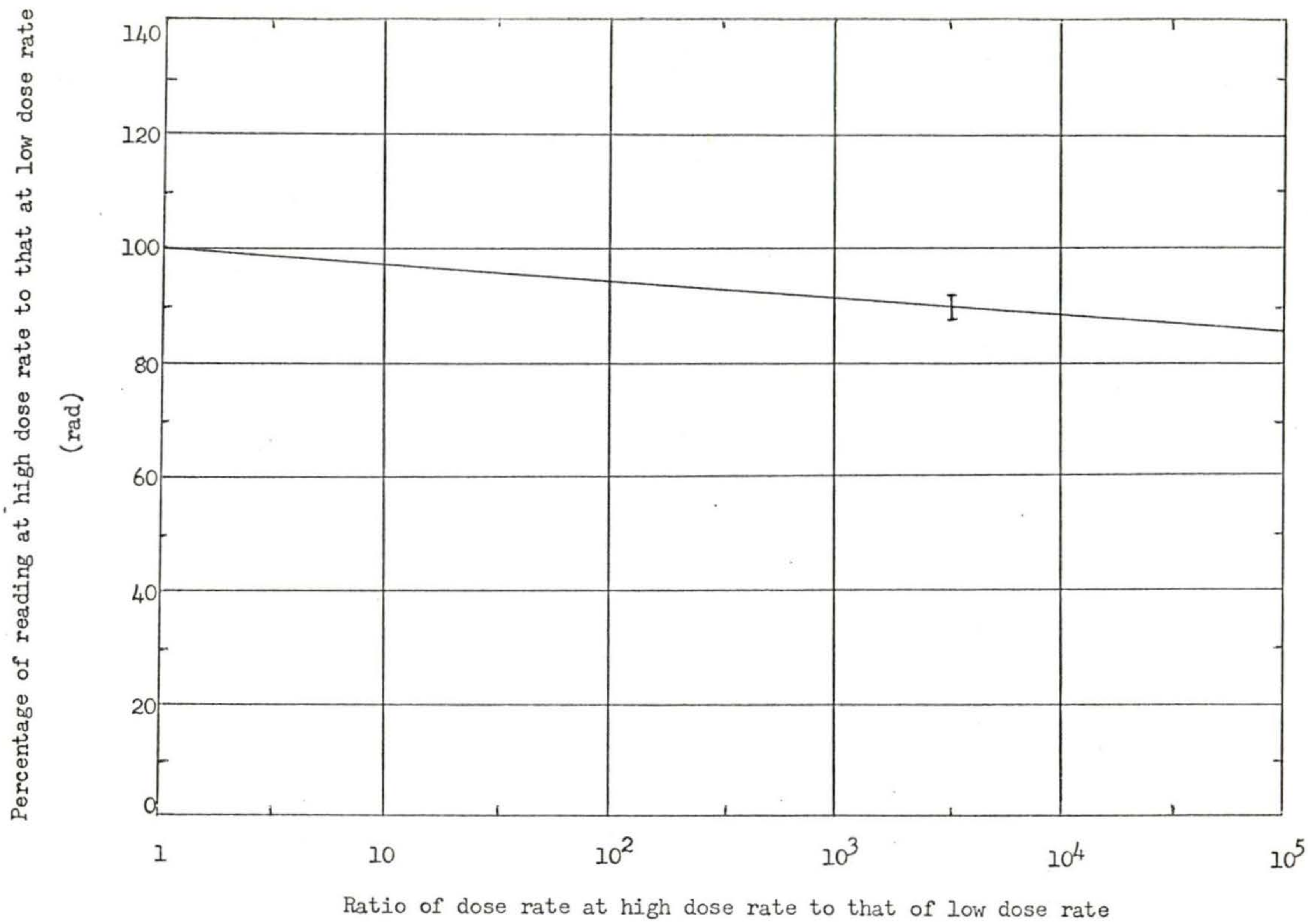

Figure 1. Dose-rate dependence curve

reduce the energy dependence of the dosimeter, a shield of 0.05 inches of lead lined with teflon or polyethylene, which reportedly gives a peak ratio of 1.6-1, was used (4). See Figure 2.

The precision of measurements with these rods will depend on the ability to reposition the rods, variation of the power level, temperature of exposure, etc. which can be associated with the experimental procedure. In addition, variation will be inherent in the dosimetry system itself--the reproducibility of reading a dosed rod. The rods were read on both ends and the average of the readings on the two ends was taken as the reading. The rods were read to only the nearest one half unit. Rods showing more than two or three units difference between the readings for the two ends were suspect for being chipped, in which case the rod was examined and the reading with the unchipped end toward the photomultiplier tube was taken. A standard deviation of 1.8% was found for a series of twenty readings, which compared quite well with the values found in previous studies of 2-3% (3, 2).

One of the shortcomings of the silver phosphate glass dosimeters is that the readings are not stable, but vary with time. Since the change in the luminescence response depends upon the dose absorbed, the preirradiation stability is no problem because the readings were taken just before irradiation, and none of the run times were long enough to give problems with change in preirradiation reading. The variation of the readings after dosing the rods is quite time dependent, increasing to a peak at 24 hours and thereafter decreasing as described by the

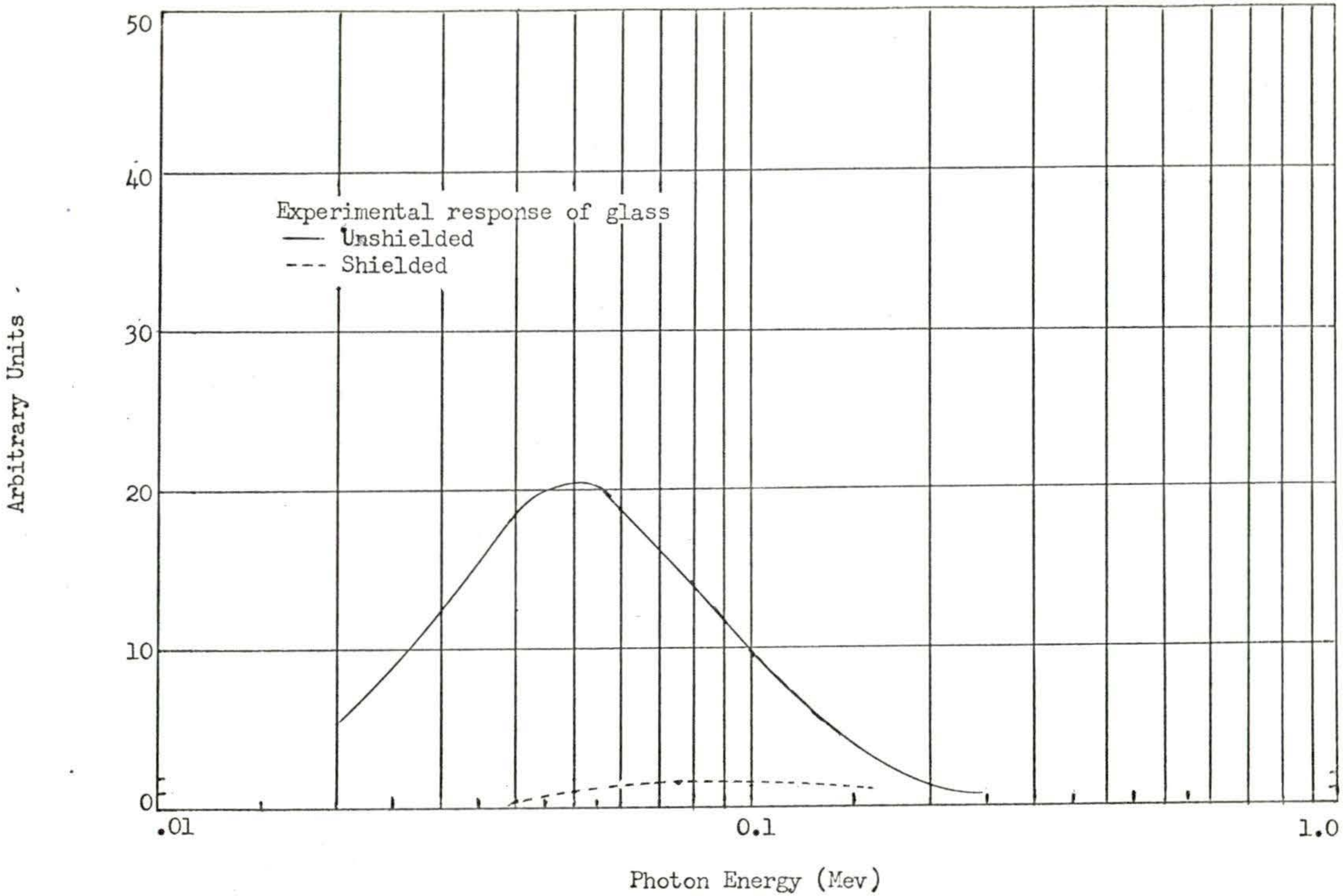

Figure 2. Experimental response of shielded and unshielded glass versus photon energy

expression[1]:

$$R_{(t)} = \left[1 - 0.0107\ (\ln t)^2\right] R_0$$

where: R_0 = reading 24 hours after irradiation

t = time after irradiation - 24 hours

The variation of the indicated dose rate with temperature is quite significant. The change is reported to be directly proportional to the temperature and is about 0.5 percent per degree centigrade (4). However, since all the rods were dosed and read at temperatures very close to 72°F, no correction was made for temperature variations.

Since the dosimeters are sensitive to thermal neutrons, showing a response which is 1.4 times as great as the 1 Mev gamma sensitivity, correction for the thermal neutron dose must be made or the dose from the thermal neutrons cut to negligible values by a shield as was done in this case by a boron shield. The response of the dosimeters to fast neutrons is only 0.007 times the 1 Mev gamma sensitivity and as a result, produces a negligible response in the rods.

The amount of orange luminescence arising from these centers upon excitation was read with a Bausch and Lomb microdosimeter reader, a specialized fluorimeter, in which the luminescence is produced by radiating the glass with ultraviolet light of 3650 A wavelength which corresponds to the peak in the absorption curve for the irradiated rods. The luminescence produced is collected by a conical reflector,

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[1]Martin, J. A., International Business Machines, Radiation effects department, Owego, New York. Time dependence of Fluorod readings. Private communication. 1964.

passed through an "orange pass" filter system to eliminate the exciting ultraviolet radiation and measured by an "end-on" measuring photomultiplier.

The calibration curve used with the microdosimeter reader is shown in Figure 3. The standards used in constructing this curve were obtained from the radiation effects department of International Business Machines.

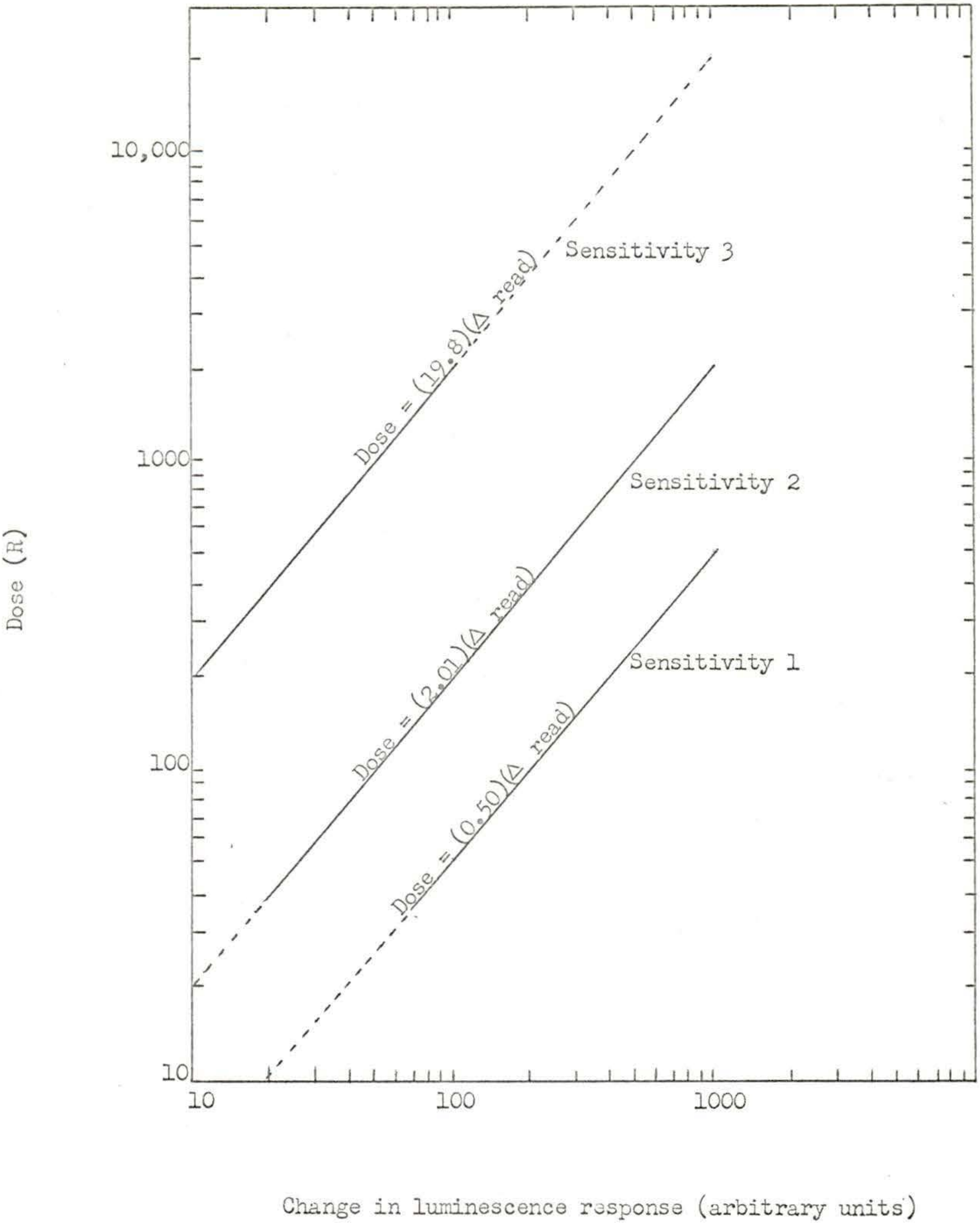

Figure 3. Calibration curve for microdosimeter reader

ANALYSIS OF PROBLEM

In describing the gamma dose rate in the rabbit, the problem was divided into four parts:

1. description of the gamma dose rate as a function of power level at the time the power level was achieved;
2. description of the increase in the gamma dose rate as a function of the operating time;
3. description of the background dose rate i.e., the gamma dose rate remaining after a previous run as a function of the conditions of that run and the time elapsed since the shutdown for that run; and
4. description of the dose rate as a function of the position in the rabbit tube and power level.

In describing the gamma dose rate as a function of the reactor power level for zero operating time, measurements have to be made at some finite time after the power level is achieved and as a result the actual zero time at power values must be calculated from the results of the dose rate build-up findings. In order to have consistent results, a run time of five minutes was used for the determinations and it was assumed that the increase would be small so that the average dose rate for the five minutes could be treated as occurring at 2.5 minutes after the power level was achieved.

Since the increase in the dose rate per hour of operation as a function of operating time can be expected to amount to only a few percent of the total gamma dose rate (1) and since the reproducibility of the Fluorod readings is also on the order of a few percent (4), it can be seen that it will be difficult to determine the type of function directly from the data taken during a run, which will best describe this increase. In determining the build-up, the data will be assumed to consist of two parts, a constant due to the prompt gammas, etc. and a time variable term. The form of the time variable part will have to be determined experimentally.

The description of the background dose rate i.e., the dose rate due to fission products from previous runs, can be done by describing the decay of the dose rate due to fission products after a run as a function of the power level, the duration of the run, and the time lapse after scram. The background dose rate for a run will then be calculated on the assumption that operation of the reactor does not affect the fission products from a previous run, in which case the background dose rate can be considered a summation of the dose rates due to fission products from previous runs.

The description of the variation of the dose rate in the rabbit will be based on the assumption that the reactor core can be approximated by an equivalent point source at some distance from the end of the rabbit nearest to the core. In order to determine whether or not any radial variation of the dose rate exists, dosimeters will be placed in planes perpendicular to the axis of the rabbit and irradiated without shields, since the introduction of enough boron to shield all the dosimeters at once would not be wise during reactor operation. It is, however, desirable to dose all the dosimeters at once so that variation of the dose rate with reactor operation time will not affect the results.

The description of the dose rate in the rabbit will then be an expression which will take each of the parts discussed above into account.

EXPERIMENTAL PROCEDURE

The preparation of the Fluorods for use consisted of the following steps:

1. The rods which had previously been used were heated to 500°C for one hour to remove any luminescence centers from previous runs.

2. The rods were rinsed in acetone, distilled water and methyl alcohol three times in succession for a total of nine rinses.

3. The pre-dose reading was taken just previous to the run in order to minimize the possibility of significant changes in the pre-dose reading.

For use, the rods were each placed in a polyethylene covering to prevent scratches, placed in a lead shield and the rod and shield placed inside a boron packet to reduce the dose from thermal neutrons to a negligible value.

The shielded dosimeter was then placed in the rabbit which had been prepared by placing a piece of polystyrene foam cut to length so that the packeted dosimeter was 1.4 cm from the inside cover of rabbit nearest to the core. A piece of foam rubber was used to hold the rabbit contents firmly in place.

The rabbit was then placed in the reactor rabbit tube and exposed for the number of minutes shown for each exposure.

The exposed rod was then rinsed again as above and the post-dose reading taken.

For run number 854C the rods were not placed in shields, but were placed between layers of polystyrene foam cut to place the rods in planes perpendicular to the axis of the rabbit at the positions indicated.

RESULTS

Evaluation of Equivalent Point Source

Assumptions:

1. That the reactor core can be approximated by an equivalent point source.

2. Gamma attenuation in the polystyrene foam in the full length of the rabbit during run number 844C is negligible.

Let Q' = hypothetical point source strength, $cm^2 R/hr$

D = distance from point source to end of rabbit

Then, based on the geometry used for run 844C, see Figure 4,

$$\frac{Q'}{4 D^2 \pi} = \text{Dose rate at plane E}$$

$$\frac{Q'}{4\pi (D + z)^2} = \text{Dose rate at plane A}$$

Average dose rates:

Plane A = 16,300 R/hr

Plane E = 26,400 R/hr

At plane A, z = 0 cm

At plane E, z = 10 cm

Ratio:

$$\frac{\text{Dose rate E}}{\text{Dose rate A}} = 1.63$$

Then,

$$\frac{Q'}{4 D^2 \pi} = 1.63 \frac{Q'}{4\pi (D + 10)^2}$$

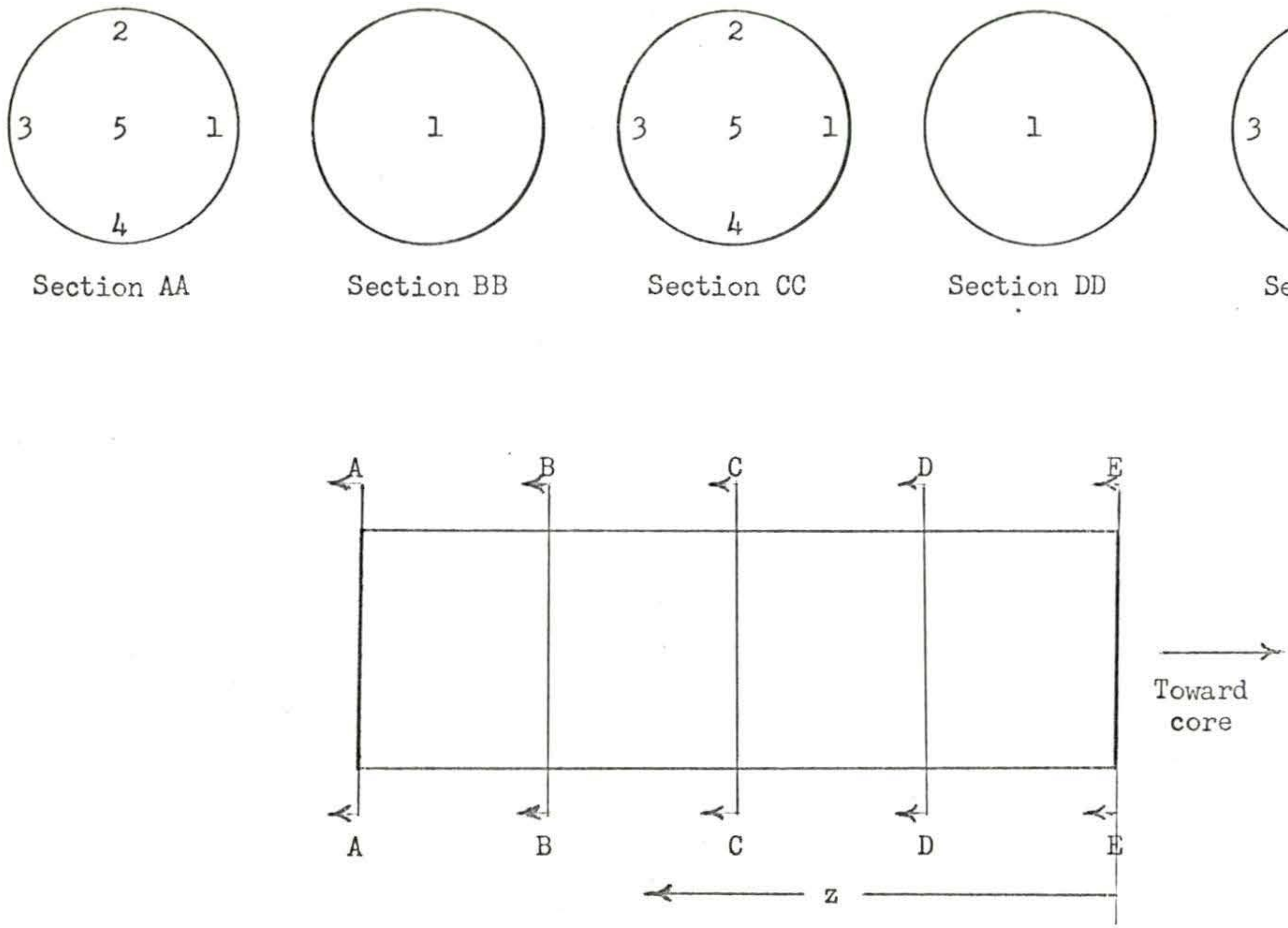

Figure 4. Dosimeter positions in the rabbit for run 854C

or

$$\frac{1}{D^2} = \frac{1.63}{(D + 10)^2}$$

$$(D + 10)^2 = 1.63\ D^2$$

$$D^2 + 20\ D + 100 = 1.63\ D^2$$

$$0.63\ D^2 - 20\ D - 100 = 0$$

$$D = \frac{20 \pm \sqrt{400 + (4)(0.63)(100)}}{(2)(0.63)}$$

$$D = 36.2 \text{ cm}$$

From this value of D, and by defining Q, as an effective source strength ie, $\frac{Q'}{4\pi}$

$$Q = (\text{Dose at plane E})(D^2)$$

Then

$$Q = (26{,}400)(36.2)^2$$

$= 3.46 \times 10^7$ R/hr at 1000 watts, 62.8 minutes after power level was achieved.

Based on these assumptions then, the dose rate at any axial position in the rabbit can be expressed by:

$$\text{Dose rate } (z) = \frac{3.46 \times 10^7}{(36.2 + z)^2}$$ R/hr at 62.8 minutes after power level was achieved

where:

z = distance measured from the inside end of the rabbit toward the core.

Table 1. Gamma dose rates as a function of position in the rabbit

Plane	A	B	C	D	E
z (cm)	10	7.5	5.0	2.5	0
$(36.2 + z)^2$	2,134	1,909	1,697	1,498	1,310
Unshielded average dose rate	16,300	18,200	19,200	22,600	26,400
Calculated dose	16,300	18,100	20,400	23,100	26,400
Percent difference	0	0.5	3.0	2.2	0

The source strength in this relationship, however, is based on the results of only one run, which was run without shields on the dosimeters. As a result the constant will have to be re-evaluated on the basis of several runs in which the dosimeters were shielded.

The data from a number of runs for dose rate versus power level is shown on Figure 5. A straight line least squares fit gives the relationship,

$$\text{Dose rate (R/hr)} = 13.4\ (\text{P. L.})^{1.00185}$$

where: P. L. = Power level in watts

which gives the dose rate at z = 1.4 cm for an average operation time of 2.5 minutes as a function of power level for power levels between 10 watts and 10,000 watts.

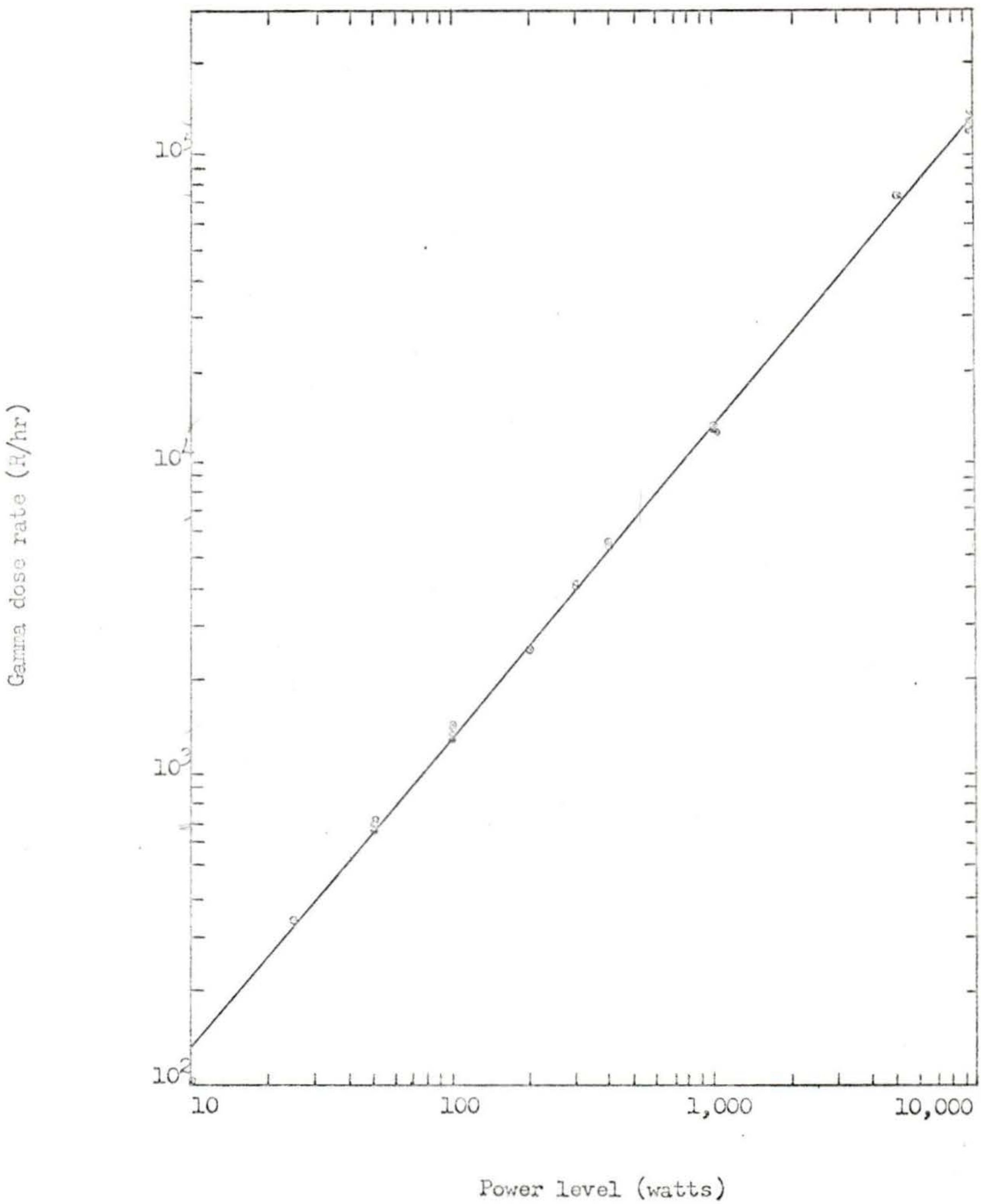

Figure 5. Gamma dose rate at 2.5 minutes after power was achieved as a function of power level

Since the calculations have been carried out to only three places, the power of the time (1.00185) was rounded off to 1.00. Then, the equivalent source strength was solved for as follows:

$$\text{Dose rate at z (R/hr)} = \frac{Q \ \text{cm}^2 \ \text{R/hr}}{(36.2 + z)^2 \ \text{cm}^2}$$

$$Q \ (\text{cm}^2 \ \text{R/hr}) = 13.4 \ (\text{P. L.})^{1.00} \ (36.2 + 1.4)^2$$

$$Q \ (\text{cm}^2 \ \text{R/hr}) = 1.82 \times 10^4 \ (\text{P. L.})$$ at 2.5 minutes after power level was achieved.

Experimental plots of the time dependent part of the gamma flux at power showed that the data gives a straight line on full logarithmic graph paper, and as a result the total gamma flux will be represented by an equation of the form:

$$\text{D. R.}_{(t)} = R_0 + kT^c$$

where:

$\text{D. R.}_{(t)}$ = Dose rate as a function of time

R_0 = quantity dependent only on the power level

k = a constant dependent only on the power level

T = time of reactor operation in minutes

c = a constant

The quantity, R_0, was taken as the average value of the dose rate at T equal to zero. This value was determined by a trial and error fitting of the individual dose rate-time curves with an extrapolation for T equal to zero. The values of k and c were also obtained from least squares fits for the individual curves.

The values of c from runs 843, 854, and 918 were 0.0943, 0.0816, and 0.0847, giving an average value of 0.0869. The values of k from runs 843, 854, and 918 were 120, 1380, and 9850. Since the value of k is dependent on the power level, the value (k/P. L.) was averaged, giving an average of 1.19 for the three runs.

The values of R_0 for the three runs were 1.42×10^3, 1.38×10^4, and 1.18×10^5. The average value of (R_0/P. L.) was found to be 13.3. The results are shown on Figure 6.

The dose rate as a function of time based on runs 843, 854, and 918 can be expressed as

$$D.\ R._{(t)} = (13.3)(P.\ L.) + (1.19)(P.\ L.)(T)^{0.0869}$$

Since the expression above is based on only the three runs 843, 854, and 918, better values of the power level dependent constants could be obtained by taking the ratio of the average dose rate at 2.5 minutes after start-up for the three runs to the average dose rate at 2.5 minutes after start-up found previously. The average value of (R_0/P. L.) for the three runs was 14.6, giving a ratio of 0.932 which was used in calculating the equivalent point source.

The equivalent point source is given by:

$$Q = \left[(13.3)(P.\ L.) + (1.19)(P.\ L.)(T)^{0.0869}\right](36.2 + 1.4)^2(0.932)$$

$$= 1.75 \times 10^4(P.\ L.) + 1.57 \times 10^3(P.\ L.)(T)^{0.0869}$$

The evaluation of the background dose rate--the dose rate due to fission products from previous runs--was based on the data taken

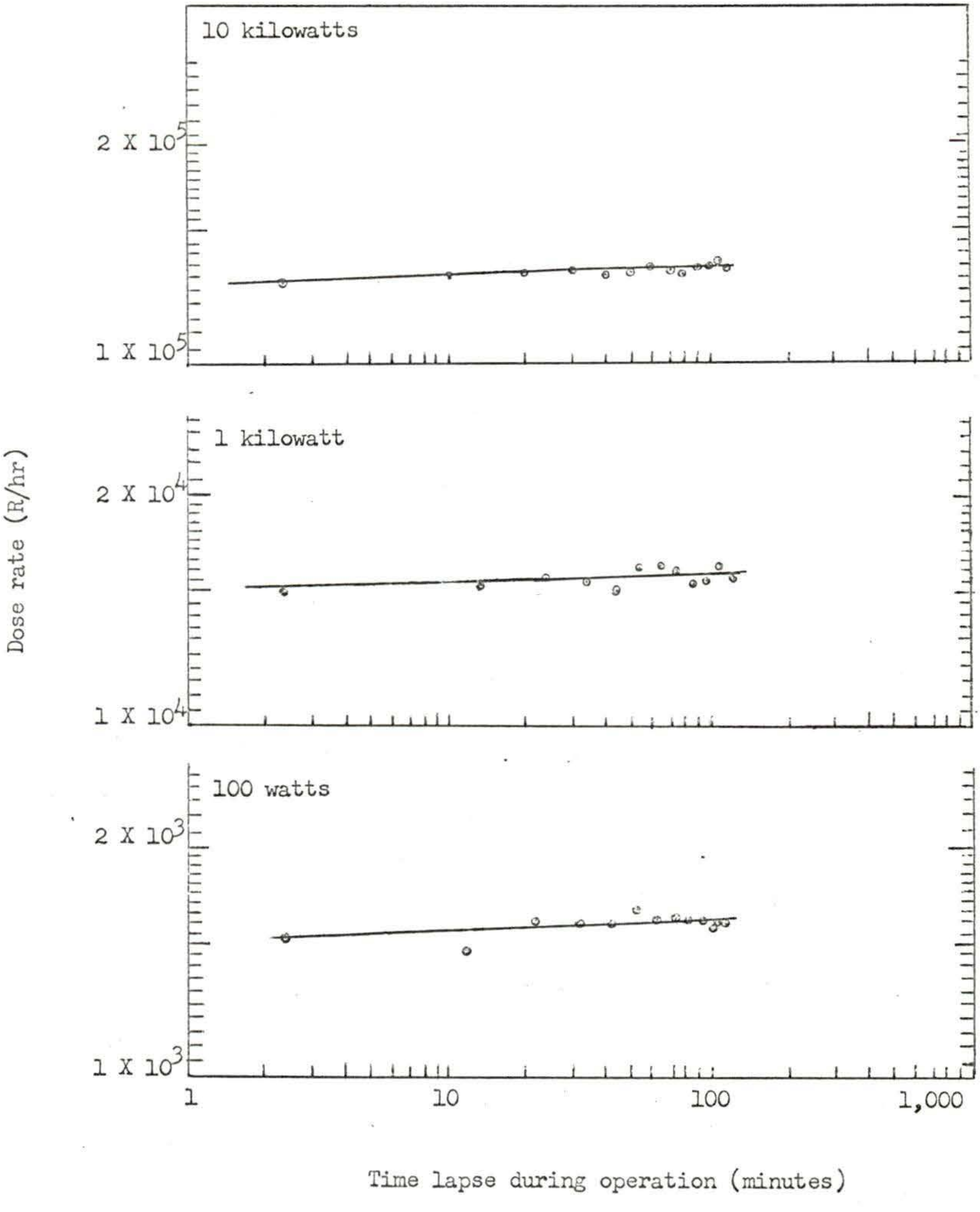

Figure 6. Dose rate as a function of time after power level was achieved

after shutdown for a number of runs. The results of these runs are shown in Figure 7 and Figure 8. The straight lines which start at one hour after shutdown shown on the figures are based on a relationship which was evaluated as follows.

A plot of the dose rate at one hour after shutdown for a series of 10 kilowatt runs is shown in Figure 9. A least square fit of the data gives the relationship

$$B_{(T)} = 235\ T^{0.618} \qquad \text{at } z = 1.4 \text{ cm}$$

where:

$B_{(T)}$ = Dose rate at one hour after shutdown

T = Duration of reactor operation in minutes

Examination of Figure 8 shows that the dose rate at one hour after shutdown is approximately directly proportional to the power level, and it will be assumed that it is exactly proportional to the power level. Then,

$$B_{(T)} = 2.35 \times 10^{-2}\ T^{0.618}\ (\text{P. L.}) \qquad \text{at } z = 1.4 \text{ cm}$$

Since the slope of the approximation lines on Figures 7 and 8 did not show any dependence upon the duration of the run at power, the decrease in the dose rates as a function of time elapsed since shutdown is given by

$$B_{(T,t)} = \frac{2.35 \times 10^{-2}\ T^{0.618}\ (\text{P. L.})}{t^{a}}$$

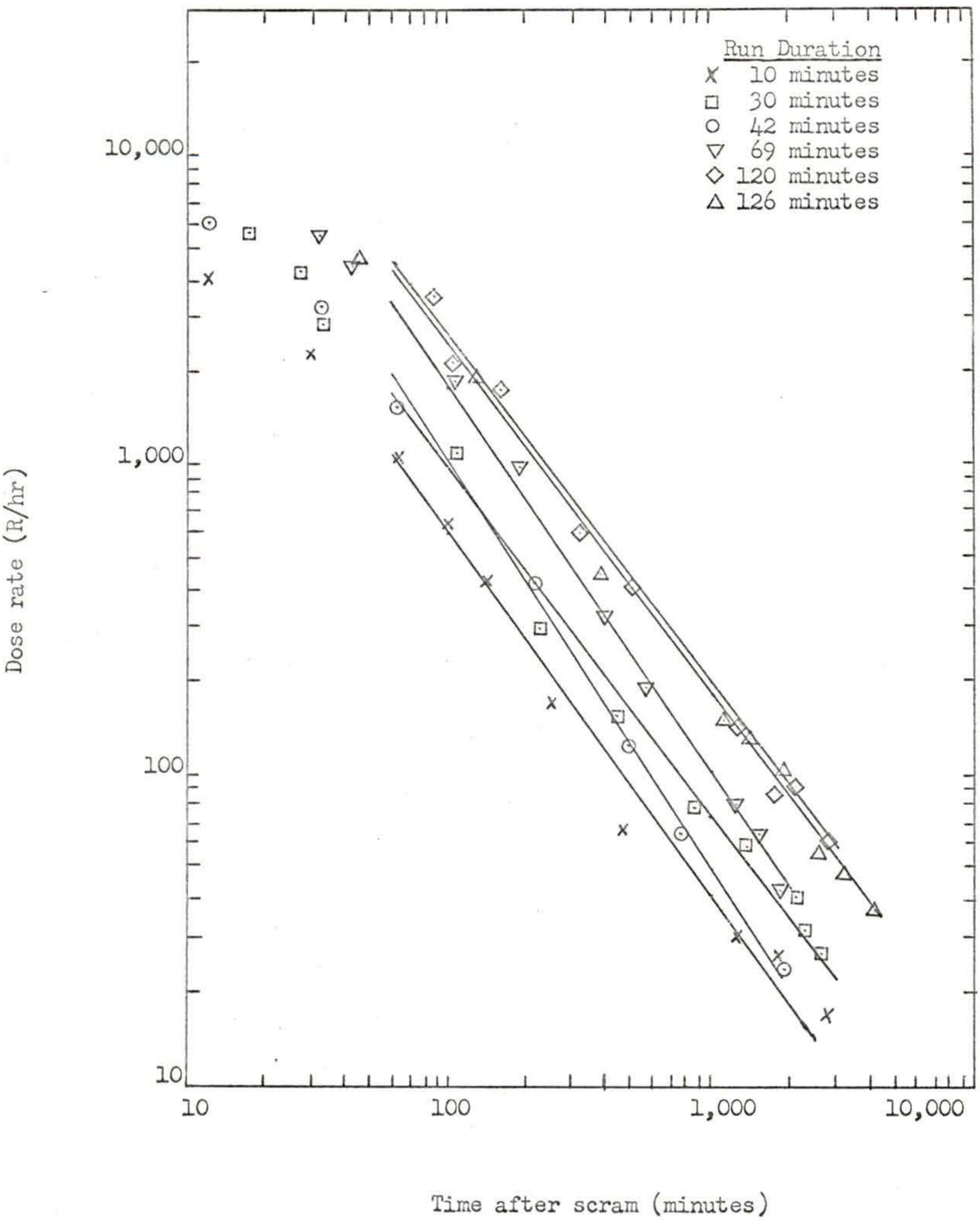

Figure 7. Dose rate as a function of time after scram for a series of 10 kilowatt runs of varying duration

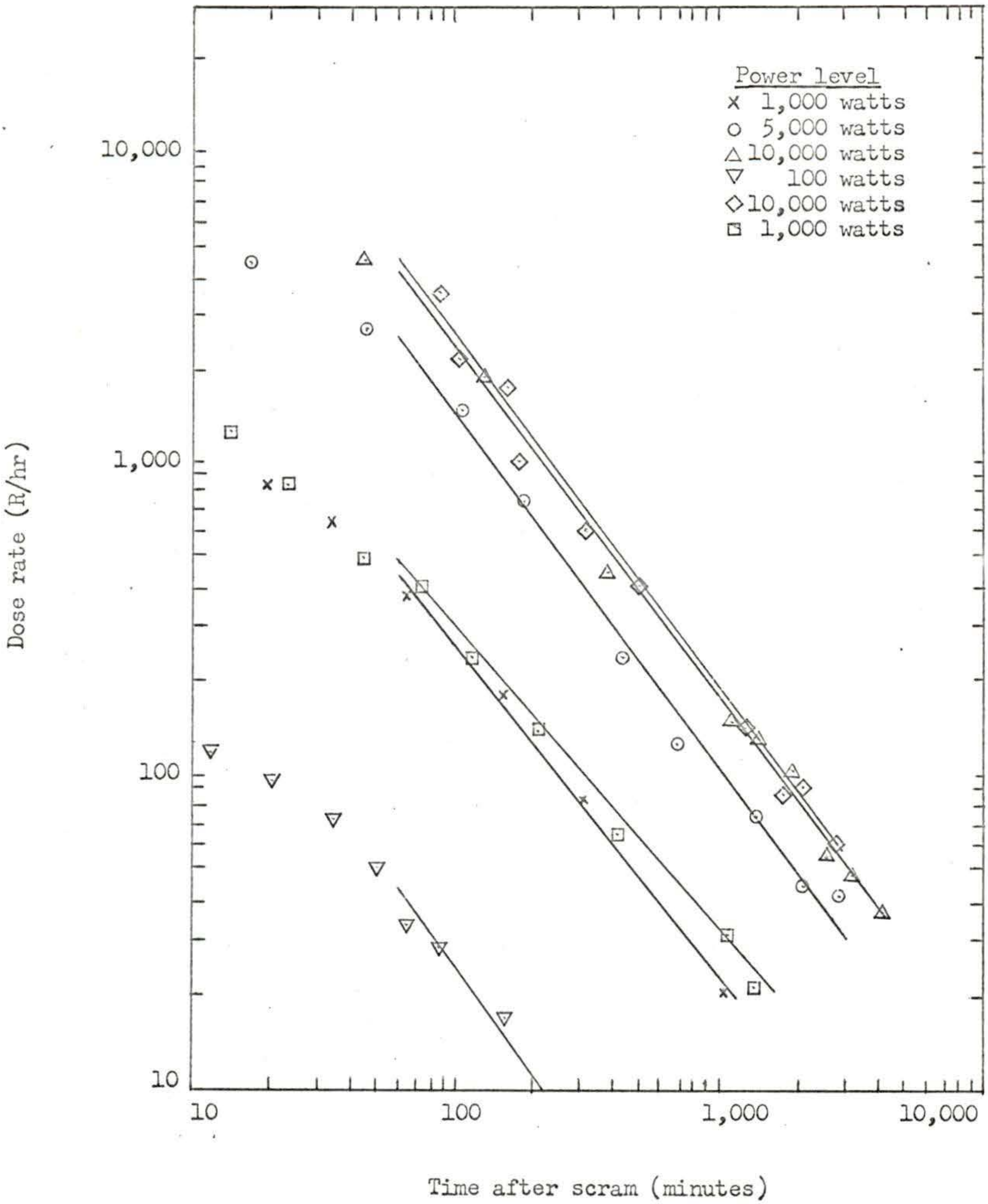

Figure 8. Dose rate as a function of time after scram for a series of two hour runs at various power levels

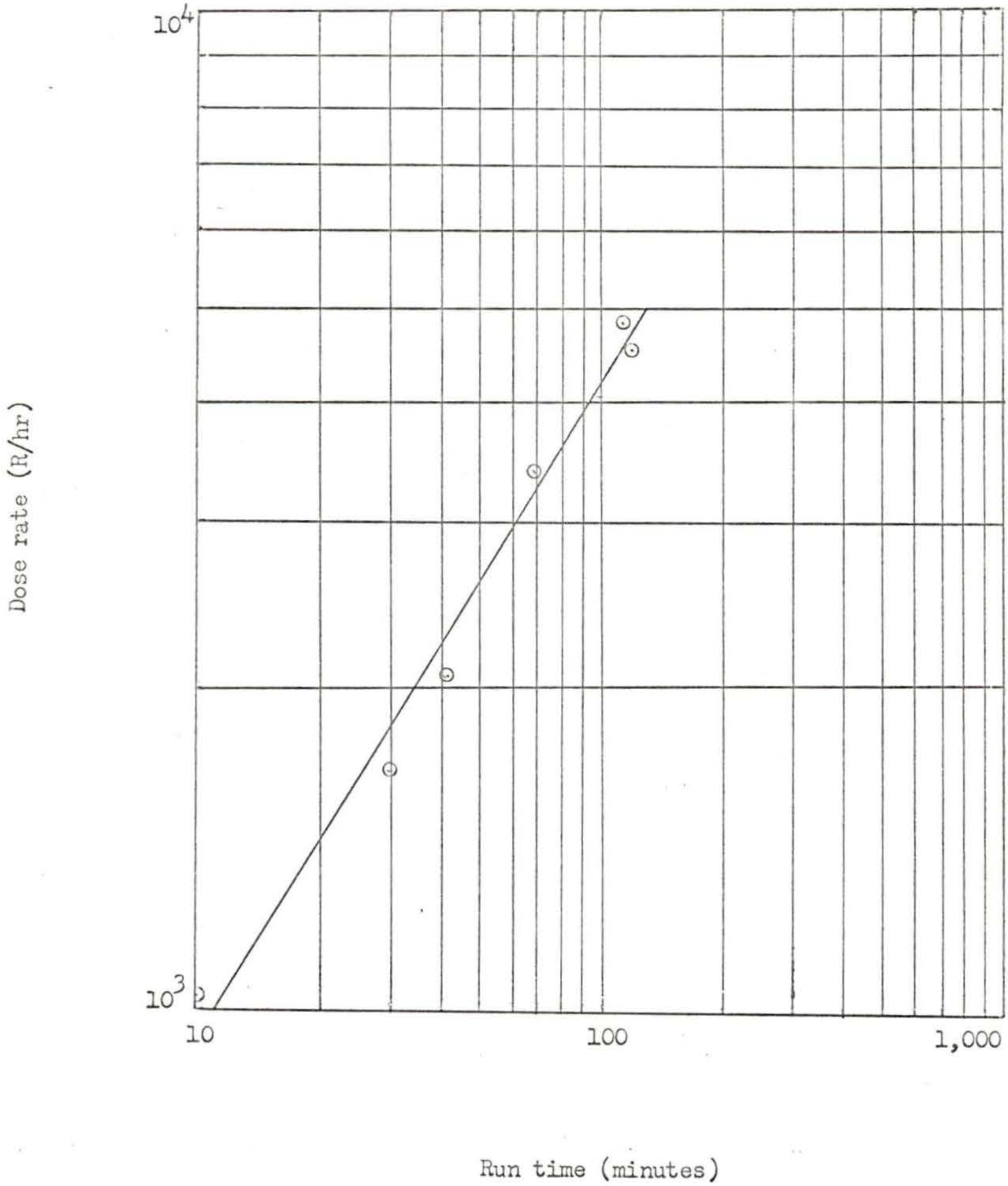

Figure 9. Gamma dose rate one hour after scram as a function of operating time at 10 kilowatts

where:

t = time elapsed since shutdown in minutes

a = the average value for all the runs = 1.08

Then, based on the assumption that the dose rate due to the fission products from previous runs can be approximated by a summation of the dose rates from previous runs, the equivalent point source is given by

$$B_{(T,t)} = \sum_n \frac{33.2\,(P.\,L.)T_n^{0.618}}{t_n^{1.08}}$$

Then,

$$\text{Dose Rate (R/hr)} = \frac{(1.75 \times 10^4)(P.\,L.) + 1.57 \times 10^3 (P.\,L.)T^{0.0869}}{(36.2 + z)^2} + \frac{\sum_n \dfrac{33.2(P.\,L.)T_n^{0.618}}{t_n^{1.08}}}{(36.2 + z)^2}$$

where:

$P.\,L.$ = Power level in watts

T = Time in minutes elapsed since power level was achieved

z = distance in cm measured from the inside end of the rabbit toward the core

T_n = Time duration in minutes of previous runs

t_n = Time in minutes elapsed since scram from each previous run

Calculation of the Standard Deviation for Reading Microdosimeters

Table 2. Data from repeated readings of one microdosimeter

Trial	End 1	End 2	Trial	End 1	End 2
Rod A-68 (multiplier 3)					
1	96.0	94.5	11	93.0	94.0
2	97.0	95.0	12	95.5	94.5
3	96.5	98.0	13	94.5	93.5
4	95.0	93.5	14	94.0	92.0
5	94.5	94.0	15	93.5	93.0
6	95.0	96.0	16	93.5	94.5
7	98.0	97.0	17	96.0	94.0
8	94.5	95.0	18	94.5	94.0
9	92.0	95.5	19	96.5	97.5
10	95.5	96.5	20	96.5	96.5

Average reading = 95.0

$\sigma = 1.8$

Reading $= 95.0 \pm 1.8$

$= 95.0 \pm 1.9$ %

Calculation of the Standard Deviation for the Dose Rate at 100 Watts

Table 3. Dose rates found from six readings of dose rates at 100 watts

Trial	Dose rate R/hr	Trial	Dose rate R/hr
1	1450	4	1490
2	1370	5	1420
3	1440	6	1340

Average dose rate = 1418 R/hr

σ = 55 R/hr

Dose rate at 100 watts = 1418 $\pm$ 55 R/hr

= 1418 $\pm$ 3.9 %

COMMENTS AND RECOMMENDATIONS

The data for power levels greater than 1,000 watts were taken based on runs of thirty seconds, while the data taken at power levels less than 1,000 watts were based on runs of five minutes duration. An attempt was made to use five minute runs for power levels greater than 1,000 watts, however, dose rates found were smaller than for thirty second runs. The dose rate recorded for a five minute, ten kilowatt run was approximately fifty percent of that found for a thirty second run. The dose rate recorded for a five minute, five kilowatt run was approximately seventy-five percent of that found for a thirty second run. This behavior is characteristic of the behavior reported for dosimeter saturation, however, the observed saturation effect was found for absorbed doses greater than approximately 10^3 R, while the saturation dose rates reported in the literature (3,4) were approximately 10^4 R. Since the standards used had a maximum dose of 2,000 Roentgens, run times of thirty seconds were used for power levels above one kilowatt.

In establishing the pre-run dose rate, several data points were taken before each run was started to establish the rate of change of the background with reference to the time lapse since the previous run and are shown at the beginning of each table unless the run was immediately preceded by another run on which data was taken. The "background" dose rate was then obtained by assuming a straight line and extrapolating to the dose rates for time lapses concurring with the data points.

The approximations for the gamma dose rate after reactor shutdown are valid for times greater than one hour after shutdown. Examination of the data plotted on full logarithmic graph paper showed a definite change in the slope of a line through the experimental data at approximately one hour after shutdown for each of the runs. As a result, the slope of the straight line approximation was based on data points for times greater than sixty minutes after scram.

Since the response of the dosimeter used in these determinations, even with the lead shield is not independent of the energy of the radiation, the actual gamma dose rate in the rabbit should be checked by another system which has a lower energy dependence. Another alternative is that some of the new shields now being experimented with, such as a combination tin-tantalum shield, which preliminary results seem to indicate have a better energy independence, might be used after more data on these shields becomes available.

The results of this report can be used to obtain an approximation of the gamma dose rate in the rabbit in roentgens per hour. A useful addition to this report would be a study of the gamma energy spectrum in the rabbit, since this would make possible better estimates of the dose which would be absorbed in an irradiated material.

The power level as reported in the data was obtained from the micro micro ammeter, using a calibration factor of one watt = 1.6×10^{-8} micro micro ampere.

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The author wishes to express his sincere appreciation to Dr. Glenn Murphy for his assistance and patience during the course of this investigation.

APPENDIX

Table 4. Gamma dose rate at 2.5 minutes after power level was achieved

Dosimeter	Duration min	Power level watts	Dosimeter reading Before scale-read	After scale-read	Δ read	Dose R	Dose rate R/hr	Background dose rate R/hr	Δ dose rate R/hr
Run 822									
L-2	20	0	1-26	1-54	28	14	49		
L-3	5	50	1-27	3-48	124	62	744	49	695
L-4	5	100	1-25	10-26	248	124	1490	49	1,450
L-5	5	400	1-23	10-89.5	917	458.5	5500	49	5,450
Run 831									
L-3	6	0	1-26	1-38	12	6	60		
L-4	5	50	1-26	3-47	122	61	732	60	672
L-5	5	100	1-34	3-86.5	238	119	1430	60	1,370
Run 843									
A-1	5	100	1-17	3-82	241	121	1440	0	1,440
Run 848									
A-41	11	0	1-17	1-24	7	3.5	18		
A-42	5.5	10	1-17	1-44	27	13.5	120	18	102
A-43	5	25	1-17	1-19	62	31	365	18	347
A-44	5	50	1-18	3-44.5	120	60	720	18	702
A-45	5	100	1-17	3-85	251	126	1510	18	1,490
A-46	5	200	1-17	10-45.5	462	231	2770	18	2,750
A-47	5	300	1-17	10-68	697	349	4180	18	4,160
A-48	5	400	1-17	10-89	918	459	5500	18	5,480

Table 4 (Continued)

Dosimeter	Duration	Power level	Dosimeter reading		Δ read	Dose	Dose rate	Background dose rate	Δ dose rate
	min	watts	Before scale-read	After scale-read		R	R/hr	R/hr	R/hr
Run 850									
A-61	10	0	1-17	1-19	2	4	24		
A-49	0.5	10,000	1-18.5	10-49.5	500	1000	120,000	24	120,000
Run 852									
A-71	5	0	1-17	1-29	12	6	66		
A-72	5	100	1-17	3-84	248	124	1,490	66	1,420
A-73	5	400	1-17	10-90	928	464	5,570	66	5,500
Run 853									
A-49	10	0	1-17	1-18.5	1.5	3	18		
A-41	0.5	10,000	1-24	10-56.5	590	1180	141,000	18	141,000
Run 854									
A-87	6	0	1- 4	1- 3	0	0	0		
A-88	5	1,000	1- 4	10-53	552	1160	13,900	0	13,900
Run 855									
A-68	10	0	1-18	1-19	1	2	12		
A- 3	0.5	5,000	1- 4	10-30	311	622	74,500	12	74,500

Table 4 (Continued)

Dosimeter	Duration min	Power level watts	Dosimeter reading Before scale-read	After scale-read	Δ read	Dose R	Dose rate R/hr	Background dose rate R/hr	Δ dose rate R/hr
Run 857									
A-49	5	0	1-27	1-29	2	4	24		
A-105	0.5	10,000	1-32	10-53.5	530	1050	127,000	24	127,000
Run 858									
A-7	16	0	1-13	1-24	11	22	83		
A-8	5	100	1-48	3-34	59	118	1,470	80	1,390
A-10	0.5	1,000	1- 7	1-61	54	108	13,200	80	13,100
Run 917									
B-15	5	0	1- 1	1- 1.5	0.5	10	120		
B-16	5	1,000	1- 5	1-58.5	53.5	1070	12,900	120	12,800
Run 918									
B-15	5	0	1- 1.5	1- 2	0.5	10	120		
B-19	0.5	10,000	1- 2.5	1-56	53.5	1070	129,000	120	129,000

Table 5. Gamma dose level after scram

Dosimeter	In time	Duration min	Time lapse min	Dosimeter reading Before scale-read	Dosimeter reading After scale-read	Δ read	Dose R	Dose rate R/hr	Background dose rate R/hr	Δ dose rate R/hr
Run 835										
February 13, 1965										
L-1	16:40	10	1438	1-13	3-19	63	30.5	91.5		
February 14, 1965										
L-4	9:35	20	2513	1-12	1-68	36	17	51		
L-5	16:20	20	2918	1-12	1-52	27	13	42		
February 15, 1965										
L-6	10:45	20	4023	1-11	1-22	12	5.5	33		
L-1	16:17	5	19.5	1-19	3-54	151	75.5	894	31	863
L-2	16:32	5	34.5	1-12	3-41	117	58.5	689	31	658
L-3	17:02	5	64.5	1-12	3-27	72.5	36.3	422	30	392
L-4	18:32	20	162	1-12	3-49	142	71	209	29	180
L-5	21:00	20	310	1-19	3-30	75.5	38	111	28	83
February 16, 1965										
L-6	9:10	20	1045	1-10	1-42	32	16	46	25	21

Table 6. Gamma dose rates after scram

Dosimeter	In time	Duration min	Time lapse min	Dosimeter reading Before scale-read	Dosimeter reading After scale-read	Δ read	Dose R	Dose rate R/hr	Background dose rate R/hr	Δ dose rate R/hr
Run 837										
February 16, 1965										
L-5	18:30	10	1595	1-20	1-32	12	6	36		
L-3	23:30	30	1905	1-54	1-84	30	15	30		
February 17, 1965										
L-6	7:45	20	2395	1-75	1-93	18	9	27		
L-6	11:25	5	17.5	1-18	10-74	761	380.5	4570	24	4546
L-2	11:55	5	47.5	1-17	10-47	486	243	2920	24	2896
L-3	13:00	5	112.5	1-17	10-27	267	133.5	1600	24	1576
L-4	14:20	5	192.5	1-17	3-46	128	64	768	23	745
L-5	18:20	15	437.5	1-17	3-46	128	64	256	22	234
L-1	22:30	20	690	1-17	3-38	103	51.5	155	21	134
February 18, 1965										
L-1	10:20	20	1400	3-38	3-62	61	30.5	92	17	75
L-1	20:30	20	2020	1-64	3-32.5	39	19.5	59	15	44
February 19, 1965										
L-4	10:50	20	2860	1-56	3-29	35.5	17.8	54	13	41

Table 7. Gamma dose rates after scram

Dosimeter	In time	Duration	Time lapse	Dosimeter reading		Δ read	Dose	Dose rate	Background dose rate	Δdose rate
		min	min	Before scale-read	After scale-read		R	R/hr	R/hr	R/hr
Run 838										
February 19, 1965										
L-4	16:55	5	47.5	3-29	10-83	780	390	4680	35	4645
L-5	18:31	5	143.5	1-32	10-33	312	156	1870	34	1836
L-1	22:30	20	390	3-32	10-40	319	159.5	477	32	445
February 20, 1965										
L-2	11:45	20	1185	3-32.5	3-71	121	60.5	182	28	154
L-1	17:00	20	1500	1-18.5	3-38	104.5	52.3	157	26	131
February 21, 1965										
L-3	00:00	20	1920	1-20	3-33	87	43.5	128	24	104
L-2	11:30	20	2610	1-19	1-74.5	60	30	86	22	64
L-5	21:00	20	3180	1-19	1-66	47	23.5	68	20	48
February 22, 1965										
L-1	12:00	20	4080	1-19	1-58	38	19	54	17	37

Table 8. Gamma dose rates after scram

Dosimeter	In time	Duration min	Time lapse min	Dosimeter reading Before scale-read	Dosimeter reading After scale-read	Δ read	Dose R	Dose rate R/hr	Background dose rate R/hr	Δ dose rate R/hr
Run 840										
February 22, 1965										
L-3	16:42	10		1-19	10-34.5	343	171.5	1029		
L-2	21:33	10		1-19	1-76	57	28.5	166		
February 23, 1965										
L-5	9:05	10		1-23	1-45	22	11	63		
L-3	10:44	5	12.5	1-17	10-98	1014	507	6080	60	6020
L-5	11:05	5	33.5	1-45	10-58	565	282.5	3380	58	3322
L-2	11:35	5	63.5	1-19	3-97	286	143	1720	57	1663
L-1	14:04	10	215	1-38	3-64	163	81.5	480	54	426
L-5	18:30	10	481	1-21	1-79	58	29	170	43	127
L-2	23:00	10	751	1-25	1-63	38	19	102	36	66
February 24, 1965										
L-3	19:30	20	1986	1-29	1-71	42	21	56	32	24
February 25, 1965										
L-5	14:55	20	3151	1-33	1-56	23	11.5	29	22	7

Table 9A. Gamma dose rates at power

Dosimeter	In time	Duration min	Time lapse min	Dosimeter reading: Before scale-read	Dosimeter reading: After scale-read	Δ read	Dose R	Dose rate R/hr	Background dose rate R/hr	Δ dose rate R/hr
Run 843										
March 4, 1965										
A-1	9:41	5	2.5	1-17	3-82	241	120.5	1440	0	1540
A-2	9:51	5	12.5	1-17	3-83	244	122	1460	0	1460
A-3[a]	10:01	5	22.5	1-17	10-37	371	185.5	2230	0	2230
A-4	10:01	5	22.5	1-17	3-90	268	134	1610	0	1610
A-5	10:11	5	32.5	1-17	3-89	263	131.5	1580	0	1580
A-6	10:21	5	42.5	1-17	3-89	263	131.5	1580	0	1580
A-7[b]	10:21	5	42.5	1-16	3-74	218	109	1310	0	1310
A-8	10:31	5.5	52.8	1-17	3-96	305	152.5	1660	0	1660
A-9[c]	10:41	5.5	62.8	1-17	10-44	446	223	2430	0	2430
A-10	10:41	5.5	62.8	1-17	3-99	295	147.5	1610	0	1610
A-11	10:51	5	72.5	1-17	3-91	269	134.5	1610	0	1610
A-12	11:02	4	83	1-17	3-73	213	106.5	1600	0	1600
A-13	11:11	5	92.5	1-17	3-84.5	249	124.5	1490	0	1490
A-14	11:21	5	102.5	1-17	3-88	260	130	1560	0	1560
A-15	11:31	4	112	1-17	3-73	213	106.5	1600	0	1600
A-16	11:37	3.5	117.8	1-17	3-64	184	92	1590	0	1590

[a]A-3 in plastic, in boron shield, not in lead shield (toward core) regular position.

[b]A-7 in plastic, not in boron shield, not in lead shield (away from core) on end.

[c]A-9 in plastic, not in boron shield, not in lead shield (toward core) regular position.

Table 9B. Gamma dose rates after scram

Dosimeter	In time	Duration min	Time lapse min	Dosimeter reading Before scale-read	 After scale-read	Δ read	Dose R	Dose rate R/hr	Background dose rate R/hr	Δ dose rate R/hr
Run 843										
March 4, 1965										
A-17	11:51	5	12.5	1-17	1-45	28	13	153	28	127
A-18	12:00	5	20.5	1-17	1-41	23	11.5	127	28	99
A-19	12:15	5	35.5	1-17	1-34	17	8.5	102	28	74
A-20	12:45	5	65.5	1-17	1-28	11	5.5	64	28	36
A-21	13:05	6	87	1-17	1-31	12	6	56	27	29
A-22	14:30	5	171.5	1-17	1-25	8	4	44	27	17
A-23	15:35	5	236.5	1-17	1-22	5	2.5	28	27	1
A-24	21:20	32	655	1-17	1-45	28	14	28	27	1
March 5, 1965										
A-25	13:10	24	1541	1-17	1-39	22	11	26	27	-

Table 10. Gamma dose rates after scram

Dosimeter	In time	Duration min	Time lapse min	Dosimeter reading Before scale-read	After scale-read	Δ read	Dose R	Dose rate R/hr	Background dose rate R/hr	Δ dose rate R/hr
Run 844										
March 5, 1965										
A-26	14:38	5	12.5	1-17	10-64	672	336	4030	13	4020
A-27	14:55	5	29.8	1-17	10-38.5	395	198.5	2380	13	2370
A-28	15:30	5	63.3	1-17	3-57	178	89	1070	13	1060
A-29	16:05	5	99.5	1-17	3-35	110	55	646	13	633
A-30	16:50	5	144.5	1-17	3-24	75.5	37.8	441	13	428
A-31	22:15	10	472	1-17	1-45.5	28.5	14.3	81.5	13	68.5
March 6, 1965										
A-32	12:10	20	1312	1-17	1-47	30	15	42	12	30
A-33	20:30	30	1817	1-16	1-56	40	20	38	12	26
March 7, 1965										
A-34	12:35	30	2782	1-17	1-50	33	16.5	29	12	17
A-35	19:00	30	3167	1-16	1-39	23	11.5	21	12	9
March 8, 1965										
A-36	10:40	20	4160	1-17	1-33	16	8	21	12	9

Table 11. Gamma dose rates after scram

Dosimeter	In time	Duration min	Time lapse min	Dosimeter reading Before scale-read	Dosimeter reading After scale-read	Δ read	Dose R	Dose rate R/hr	Background dose rate R/hr	Δ dose rate R/hr
Run 849										
March 15, 1965										
A-52	15:51	5	32.5	1-17	10-90	928	464	5560	38	5520
A-53	16:01	5	42.5	1-17	10-74	760	380	4560	38	4520
A-54	17:02	5	103.5	1-17	10-33	330	165	1980	37	1940
A-55	18:35	6.5	197.3	1-17	3-72	210	105	969	36	933
A-56	21:55	10	399	1-17	3-43.5	120	60	360	35	325
March 16, 1965										
A-57	00:30	15	556.5	1-17	3-42	115	57.5	230	33	197
A-58	10:50	15	1276	1-17	1-72	55	27.5	110	30	80
A-59	14:25	40	1504	1-17	3-45	126	63	94.5	28	66.5
A-60	20:25	30	1859	1-17	1-83	66	33	68	26	42

Table 12. Gamma dose rates after scram

Dosimeter	In time	Duration min	Time lapse min	Dosimeter reading Before scale-read	Dosimeter reading After scale-read	Δ read	Dose R	Dose rate R/hr	Background dose rate R/hr	Δ dose rate R/hr
Run 850										
March 17, 1965										
A-62	13:07	5	88.5	1-17	10-59	617	308.5	3710	46	3660
A-63[a]	13:24	6	106	1-17	10-43	450	225	2250	45	2200
A-64	14:23	10	167	1-17	10-60.5	633	316.5	1890	44	1850
A-65	16:25	5	186.5	1-17	3-56	174	87	1040	44	1000
A-66	21:00	10	564	1-17	3-49	152	76	457	40	417
March 18, 1965										
A-67	18:30	15	1278.5	1-17	3-36	92	46	178	32	145
A-68	16:20	15	1748.5	1-17	1-77	60	30	114	25	89
A-69	22:00	15	2088.5	1-17	1-75	58	29	111	19	92
March 19, 1965										
A-70	10:10	30	2809	1-17	1-95	78	39	74	13	61

[a]Water pumped up.

Table 13. Gamma dose rates after scram

Dosimeter	In time	Duration min	Time lapse min	Dosimeter reading Before scale-read	Dosimeter reading After scale-read	Δ read	Dose R	Dose rate R/hr	Background dose rate R/hr	Δ dose rate R/hr
Run 853										
March 19, 1965										
A-74	19:30	10	242	1-17	3-34	92	46	276		
A-75	24:00	10	512	1-12	1-52	40	20	120		
March 20, 1965										
A-76	9:10	20	1072	1-12	1-66	50	25	75		
A-77	10:39	5	17.5	1-17	10-94	970	485	5820	68	5750
A-78	10:49	5	27.5	1-17	10-70.5	723	361.5	4340	67	4270
A-79	11:05	6.5	34.3	1-17	10-64	655	327.5	3020	67	2950
A-80	12:13	5	111.5	1-17	3-70	204	102	1230	63	1170
A-81	14:10	5	228.5	1-17	1-76	59	29.5	357	60	297
A-82	17:30	34	443	1-17	3-81	238	119	216	52	164
March 21, 1965										
A-83	00:45	30	876	1-17	3-41	112	56	127	48	79
A-84	10:20	30	1451	1-17	3-39.5	107	52	102	44	58
A-85	19:50	50	2031	1-17	3-39.5	107	53.5	69	38	41
A-86	23:40	50	2251	1-17	3-39	105	52.5	66	34	32
March 22, 1965										
A-81	7:00	60	2696	1-76	3-54	90	45	56	29	27

Table 14A. Gamma dose rates at power

Dosimeter	In time	Duration min	Time lapse min	Dosimeter reading Before scale-read	Dosimeter reading After scale-read	Δ read	Dose R	Δ Dose rate R/hr
Run 854								
March 22, 1965								
A-87	13:33	6	-	1-4	1-3	0	0	0
A-88	14:50	5	2.5	1-4	10-53	552	1160	14,900
A-89	15:02	5	14.5	1-4	10-58.5	610	1280	15,400
A-90	15:12	5	24.5	1-4	10-57.5	600	1260	15,700
A-91	15:22	5	34.5	1-4	10-59	616	1290	15,500
A-92	15:32	5	44.5	1-4	10-58	595	1250	14,900
A-93	15:42	5	54.5	1-4	10-61.5	643	1350	16,200
A-94	15:52	5	64.5	1-4	10-61.5	643	1350	16,200
A-95	16:02	5	74.5	1-4	10-60	626	1320	15,800
A-96	16:15	5.5	87.8	1-4	10-64	668	1400	15,300
A-97	16:25	5	97.5	1-4	10-59	616	1290	15,500
A-98	16:35	5	107.5	1-4	10-62	647	1360	16,300
A-99	16:45	5	117.5	1-4	10-59	616	1290	15,500

Table 14B. Gamma dose rates after scram

Dosimeter	In time	Duration min	Time lapse min	Dosimeter reading: Before scale-read	Dosimeter reading: After scale-read	Δ read	Dose R	Dose rate R/hr	Background dose rate R/hr	Δ dose rate R/hr
Run 854										
March 22, 1965										
A-100	17:02.5	5	15	1-4	1-61	57	114	1730	38	1330
A-101	17:10	6	23	1-4	1-48	44	88	880	38	842
A-102	17:30	6	43	1-4	1-31	27	54	540	38	502
A-103	17:57	8	71	1-4	1-36	32	64	480	38	442
A-106	18:50	10	125	1-4	1-29	25	50	300	37	263
A-104	20:10	20	210	1-4	1-34.5	30.5	61	183	37	146
A-105	23:20	33	406.5	1-4	1-31.5	27.5	55	100	35	65
March 23, 1965										
A- 74	10:20	42	1131	1-4	1-25	21	42	60	29	31
A- 49	16:35	34	1442	1-4.5	1-19	14.5	29	51	27	24

Table 14C. Geometric distribution of gamma dose rates in rabbit

Plane	Dosimeter	Dosimeter reading Before scale-read	Dosimeter reading After scale-read	Δ read	Dose R	Dose rate (R/hr) X 10^{-4}
Run 854C[a]						
A	1	1-1	10-37	387	813	1.63
A	2	1-18	10-38	380	798	1.59
A	3	1-6	10-37.5	387	812	1.62
A	4	1-3	10-37.5	390	819	1.64
A	5	1-34	10-38.5	369	775	1.65
B	1	1-1	10-48.5	469	938	1.88
C	1	1-2	10-46.5	490	980	1.96
C	2	1-9	10-48.5	479	958	1.92
C	3	1-5	10-49	491	982	1.96
C	4	1-7	10-48	475	950	1.90
C	5	1-8	10-46	448	896	1.89
D	1	1-10	10-52	535	1124	2.25
E	1	1-10	10-61	630	1322	2.64
E	2	1-8	10-60.5	626	1321	2.62
E	3	1-36	10-63.5	629	1321	2.64
E	4	1-45	10-65	635	1332	2.67
E	5	1-35	10-62.5	630	1322	2.64

[a]All data for Run 854C are for bare unshielded dosimeters.

Table 14C (Continued)

Plane	Dosimeter	Dosimeter reading		Δ read	Dose	Dose rate
		Before scale-read	After scale-read		R	(R/hr) X 10^{-4}
A	1	3-16	10-43.5	387	813	1.63
A	2	3-20	10-44	360	756	1.51
A	3	3-16	10-45	402	844	1.69
A	4	3-14	10-43.5	393	825	1.65
A	5	3-7	10-43.5	414	870	1.24
B	1	3-17	10-49.5	468	936	1.87
C	1	3-20	10-49.5	405	964	1.93
C	2	3-17	10-50	499	994	1.99
C	3	3-17	10-49	489	973	1.94
C	4	3-17	10-49.5	494	984	1.97
C	5	3-14	10-50	448	1014	2.03
D	1	3-17	10-59	539	1132	2.26
E	1	3-8	10-63	636	1336	2.67
E	2	3-15	10-65	625	1314	2.63
E	3	3-10	10-62	630	1324	2.65
E	4	3-5	10-63	615	1292	2.58
E	5	3-11	10-63	627	1317	2.63

Table 15. Gamma dose rates at power

Dosimeter	Duration min	Time lapse min	Dosimeter reading Before scale-read	 After scale-read	Δ read	Dose R	Dose rate R/hr
Run 918							
June 8, 1965							
B-15	5	-	1- 1.5	1- 1.5	0	0	0
B-19	.5	2.5	1- 2.5	1-56	53.5	1070	128,000
B-20	.5	10.0	1- 4	1-58	54	1080	130,000
B-21	.5	20.0	1- 1.5	1-56	54.5	1090	131,000
B-22	.5	30.0	1- 1.5	1-56.5	55	1100	132,000
B-23	.5	40.0	1- 4	1-58	54	1080	130,000
B-24	.5	50.0	1- 4	1-58.5	54.5	1090	131,000
B-25	.5	60.0	1- 3.5	1-59	55.5	1110	133,000
B-26	.5	70.0	1- 4.5	1-59.5	55	1100	132,000
B-27	.5	80.0	1- 6.5	1-61	54.5	1090	131,000
B-28	.5	90.0	1- 9.5	1-65	55.5	1110	133,000
B-29	.5	100.0	1- 4	1-60	56	1120	134,000
B-30	.5	110.0	1-17	1-72.5	55.5	1130	135,000
B-31	.5	120.0	1-40	1-95	56	1120	134,000

Table 16. Determination of neutron flux inside the boron shield[a]

Foil number	In time	Duration min	Power level a	watts	Counts	Count time min	Count rate c/m	Background count rate c/m	Corrected count rate c/m
37[b]	15:56	10	1.6×10^{-6}	100	72,241	5	14,448	17	14,431
38[c]	16:11	10	1.6×10^{-6}	100	59,218	5	11,844	14	11,830

[a]Conversion factor for count rate to neutron flux:

$$\text{neutron flux (neutrons/cm}^2\text{ sec)} = \frac{\text{saturated foil activity (cpm)}}{2.55}$$

[b]Gold foil weight = 0.0627 g

[c]Gold foil weight = 0.0626 g, exposed with cadmium cover